

# Surface Characterization of Paper Products *via* a Stylus-type Contact Method

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Surface properties include both surface roughness and friction. With a stylus-type contact method, it is necessary to obtain either a surface roughness profile or a friction profile that is affected by stylus shape and size, its contact force on the sample, the scan speed, and the data acquisition rate. As a new surface parameter, the mean absolute deviation (MAD) from an average property has been introduced. It represents the deviation from either the roughness average ( $R_a$ ) and the average coefficient of friction (COF), respectively. While  $R_a$  or average COF depends on the instrument and its operating conditions, the MAD should not depend on them because it represents the variations within the sample.

*Keywords:* Surface roughness; Friction; Surface profile; Stylus; Mean absolute deviation; MAD; R-MAD; F-MAD; Paper products

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## INTRODUCTION

Surface characterization is important and has many applications in the paper industry. As such, surface characterization is necessary in developing a papermaking process, *e.g.*, wet-end chemistry, drying, coating, printing, embossing, and laminating (Pino *et al.* 2010; Samyn *et al.* 2011; Schlegel *et al.* 2011). All these processes involve contact between at least two surfaces; therefore, their surface characterization is important. Surface characterization is also necessary to improve the qualities of a product, *e.g.*, the bulk, strength, printability, adhesion, and wettability (Ko *et al.* 1981; Hollmark 1983a, 1983b; Hodgson and Berg 1988; Ampulski *et al.* 1991; Modaressi and Garnier 2002; van Kuilenburg *et al.* 2013; Wang *et al.* 2018; Ko *et al.* 2019).

Surface properties include both roughness, and friction. The former is static and topographical and describes the geometry of the surface (ISO 13565-1 1996; ISO 3274 1996; ISO 4287 1997).

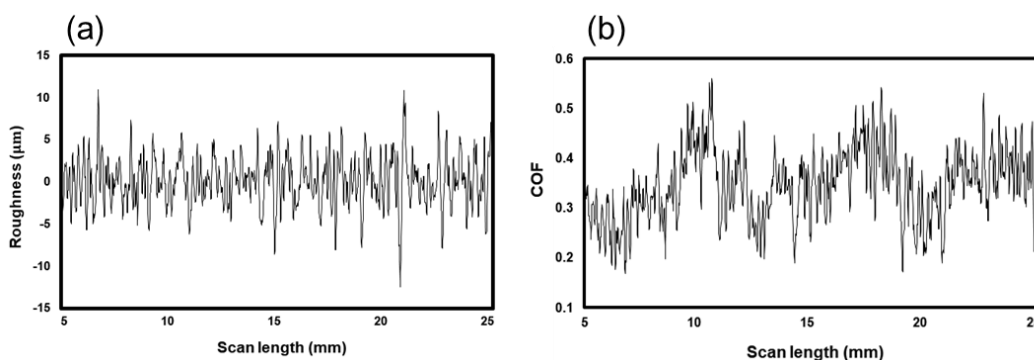
In determining the surface roughness of paper and paperboard, three types of the methods are currently available: non-contact type, indirect type, and contact type (Jeong *et al.* 2019). Meanwhile, only a contact type may be used to determine surface friction.

The optical-profiler or laser-profiler method belongs to this group (Léger *et al.* 1975; Hladnik and Lazar 2016). These methods do not touch the surface of a sample, so they are non-destructive. In addition, the highest magnified image can be obtained *via* this method. Thus, this method can characterize the surface roughness even to the smallest scale, *i.e.*, nano- to submicron (Xie *et al.* 2006). However, a trade-off exists that it can only characterize a minute sample area.

The air-leak methods belong to this type. The Bendtsen (ISO 8791-2 2013); Sheffield (ISO 8791-3 2017); Print-surf (Parker 1971; ISO 8791-4 2007); and the Oken methods (ISO 8791-5 2020) have been established as ISO standard methods. For these methods, however, the surface roughness is not measured directly; rather, it is estimated indirectly *via* comparison with a reference sample. Accordingly, the corresponding values of a reference sample may be necessary to interpret the results. For these methods, the air-leaks are assumed to occur only due to the surface roughness. This may not be necessarily true because the potential of structural parameters, *e.g.*, the pore size and distributions, influencing the air-flow are not taken into consideration.

Meanwhile, a direct contact method between a stylus (probe) and a sample surface should be preferable for paper and paperboard because a papermaking process as well as an evaluation of the quality of a product requires the contact between the product and the instrument used for testing (Yokura *et al.* 2004; Persson 2007; Beuther *et al.* 2012; Goedecke *et al.* 2013; Ko *et al.* 2019). Therefore, as direct contact method, a stylus-type contact method has been widely used. In this method, a stylus contacts the sample surface and scans along a predetermined direction.

At present, no clear relationship between the roughness and friction of paper has been established (Ko *et al.* 2019). One of the main reasons is presumably due to a lack of an instrument that can generate both profiles at the same time using the same stylus. However, recently, Kato Tech Company in Osaka, Japan has introduced a surface tester capable of generating such profiles (Kato Tech Co. 2018a,b). Figure 1 shows the surface roughness profile and friction profile of a printing and writing (P&W) paper as an illustration obtained using the Kato surface tester. In this method, a stylus shape and size, a contact force of the stylus to the surface, the scan speed, and the data collection speed have been identified as the key parameters responsible for obtaining such a profile (Kawabata 1980; Yokura *et al.* 2004; Beuther *et al.* 2012; Hanaor *et al.* 2013; Zhai *et al.* 2016; Zhai *et al.* 2017; Ko *et al.* 2019).



**Fig. 1.** Surface profile of P&W paper (a: roughness profile; b: friction profile)

#### *Determination of surface roughness*

As a surface roughness parameter, the roughness average ( $R_a$ ) has been widely used (Kawabata 1980; Leach 2010).

The  $R_a$  can be calculated according to Eq. 1,

$$R_a = \frac{1}{N} \sum_1^N |R_i| \quad (1)$$

where  $R_a$  is the roughness average ( $\mu\text{m}$ ),  $R_i$  is the roughness ( $\mu\text{m}$ ) at a point  $i$  and  $N$  is the number of data points in the scan length.

In the present study, the roughness mean absolute deviation (R-MAD) from the roughness average,  $R_a$ , was calculated according to Eq. 2,

$$R-MAD = \frac{1}{N} \sum_1^N |R_i| - R_a \quad (2)$$

Figure 2 is a graphical representation of  $R_i$ ,  $R_a$ , and R-MAD. In the figure, R-MAD is calculated from dividing the shaded area by the scan length and it is shown as the dotted lines. It is noted that R-MAD should not be the same as  $R_a$ .

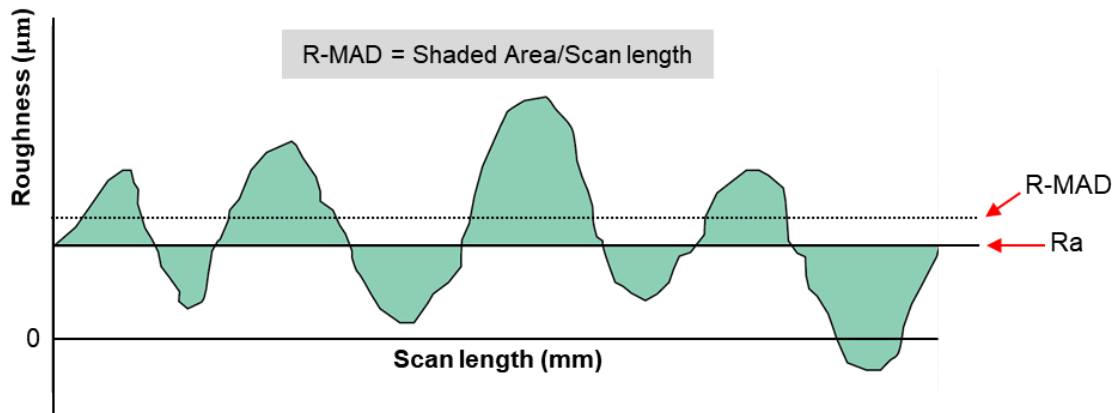


Fig. 2. A graphical representation of surface roughness parameters

#### Determination of friction

As a surface friction parameter, a coefficient of friction (COF) is generally determined by measuring the drag force when the stylus moves horizontally on the sample surface under the contact force, namely:

$$COF = \text{drag force} / \text{contact force} \quad (3)$$

At present, most of the commercial surface friction testers measure the COFs on several locations on the sample surface, then calculate the average value of COF with the standard deviation. Accordingly, they are also referred to as COF testers.

In the present study, however, in determining the surface friction, the authors have used the sample principles as those used for determining the surface roughness from a surface roughness profile. The average coefficient of friction is calculated according to Eq. 4. Then, F-MAD from the average COF has been calculated according to Eqs. 4 and 5,

$$\bar{\mu} = \frac{1}{N} \sum_1^N \mu_i \quad (4)$$

$$F-MAD = \frac{1}{N} \sum_1^N |\mu_i - \bar{\mu}| \quad (5)$$

where  $\bar{\mu}$  is the average COF,  $N$  is number of data points from the scan length,  $\mu_i$  is the COF at point  $i$ , and  $F-MAD$  is the mean absolute deviation from the average COF.

Figure 3 is a graphical representation of COF, average COF and  $F-MAD$ . In the same way of determining R-MAD,  $F-MAD$  is calculated by dividing the shaded area by the scan length and it is shown as the dotted lines.

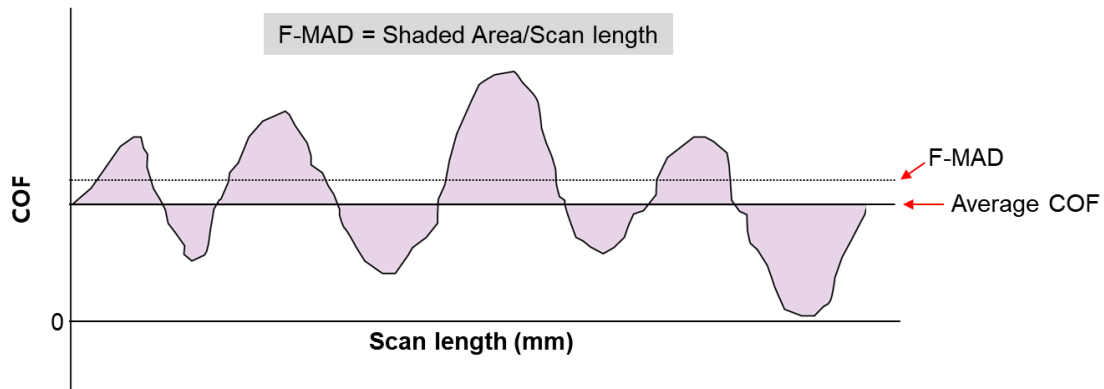


Fig. 3. A graphical representation of friction parameters

The objective of this study was to examine the relations between surface roughness and friction by stylus contact method. It was also to examine the parameters responsible for generating surface profiles. Lastly, it was to introduce the MAD, as determined from the average values, as a surface characterization parameter of paper products; the *R*-MAD for the surface roughness and the *F*-MAD for the surface friction, respectively.

## EXPERIMENTAL

### Materials

Seven paper samples with different grades were conditioned for longer than 48 h at a temperature of  $23\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$  and a relative humidity (RH) of  $50\% \pm 2\%$ , according to ISO standard 187 (1990). Table 1 shows a list of the samples, as well as their basis weight, thickness, and density.

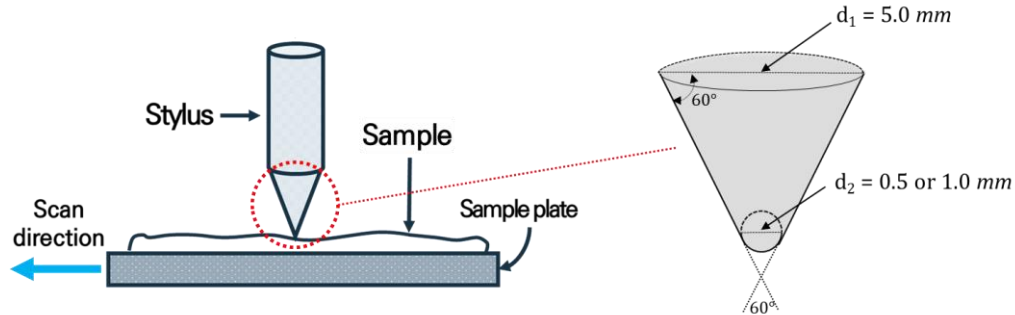
Table 1. Physical Properties of Samples

Code	Type	Basis Weight (g/m <sup>2</sup> )	Thickness (μm)	Density (g/cm <sup>3</sup> )	
R1	P&W	79.8	89.2	0.90	
R2	P&W	52.7	56.8	0.93	
R3	Newsprint	46.1	48.9	0.94	
R4	Liner	172.0	242.2	0.71	
R5	Kraft	79.6	110.2	0.72	
R6	Glossy paper	Base	333.6	410.0	0.81
R7		Coated	355.3	421.5	0.84

### Methods

The surface tester (KES-SESRU, Kato Tech Co., Ltd., Kyoto, Japan) was used. Using the same stylus both the surface roughness and the friction profiles were obtained at the same time. The stylus was made from a stainless steel (NAK 80). Its shape is conical whose tip diameter ( $d_2$ ) is shown in Fig. 4. Figure 4 also shows that the sample plate, not the stylus, moves in the scan direction.

Table 2 shows the test conditions used for determining surface roughness and friction of the samples. For each sample, 10 measurements were taken in the machine direction (MD) and the cross-direction (CD), respectively. The testing was performed at  $23\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$  and at a RH of  $50\% \pm 2\%$ .



**Fig. 4.** Configuration of the surface tester and geometry of conical type stylus

**Table 2.** Test Conditions for Surface Characterization

Run no.	Contact Force (gf)	Stylus Tip Diameter (mm)	Data Acquisition Rate (Hz)	Scan Speed (mm/sec)	Scan Length (mm)
1	3	0.5	100	1	20
2	5				
3	1	1.0	100		
4	3				
5	5		10, 100, 1000		
6	7				
7	10				

## RESULTS AND DISCUSSION

### Effects of Variables Affecting Surface Profiles

#### *Stylus size*

The tip diameter of 0.5 mm ( $d_2$ ) in Fig. 4 was unsuccessful for testing the samples except for R1 and R2 at the contact force of 3 gf or 5 gf. This result is similar to behavior of the truncated pyramid as reported by Jeong *et al.* (2019). Meanwhile, the tip diameter of 1.0 mm ( $d_2$ ) was successful for testing all samples.

#### *Data acquisition rate and spacing distance*

Spacing distance (SD) is defined as the distance between two adjacent points on the X-axis of a surface profile. It is determined according to Eq. 6,

$$SD = L/N \quad (6)$$

where SD is the spacing distance (mm),  $L$  is the scan length (mm), and  $N$  is the number of data points in  $L$  (mm).  $N$  is determined according to Eq. 7,

$$N = dar \times L/V \quad (7)$$

where  $dar$  is the data acquisition rate (Hz (or points/s)) and  $V$  is the scan speed (mm/s). Substituting Eq. 7 into Eq. 6 yields Eq. 8:

$$SD = (L \times V)/(V/dar) = V/dar \quad (8)$$

Spacing distance may be interpreted as the resolution of the X-axis in a surface profile and as such, a higher resolution indicates a shorter spacing distance (Hanaor *et al.* 2013). In Eq. 9, it is noted that the stylus size is not involved in determining the SD. Rather, it indicates that a shorter SD can be obtained by increasing the data acquisition rate. For example, the SD would be 0.1 mm (100 microns) at a  $dar$  of 10 Hz (points/s) and 0.01 mm (10 microns) at a  $dar$  of 100 Hz, with a scan speed of 1 mm/s.

Among these three  $dars$  of 10 Hz, 100 Hz, and 1000 Hz, a  $dar$  of 100 Hz, corresponding to a spacing distance of 10 microns provided the most stable, reproducible surface profiles.

### Contact force

Generally speaking, if a contact force was too high, the sample tended to be damaged or torn off. If the contact force was too low, the stylus did not touch the sample surface, making it impossible to collect data.

Figure 5 shows the plots of average COF vs. contact forces of the three samples (R1, R5, R7) in Table 1, it seems that a contact force of 5 gf provided the most reproducible results. Consequently, a contact force of 5 gf was used to determine the surface properties in the present study.

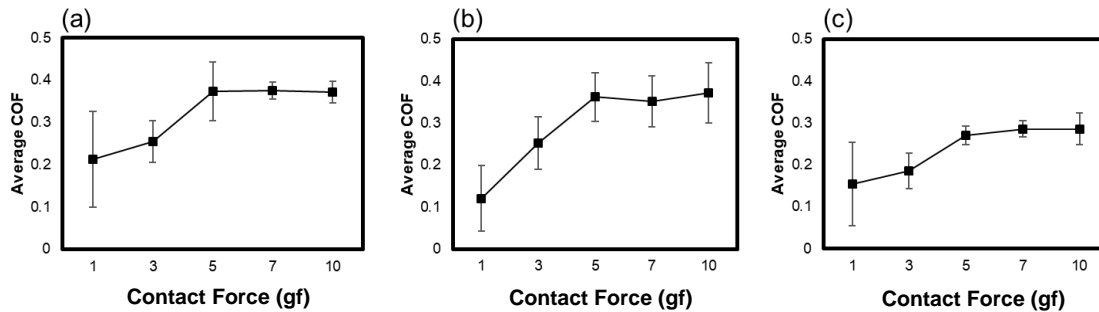


Fig. 5. Effect of contact force on surface friction (a: R1, b: R5, c: R7)

### Determination of Surface Roughness

The  $R_a$  and  $\underline{R}$ -MAD were calculated using Eqs. 1 and 2, respectively. The coefficient of variation (COV) in percentage was determined from 10 measurements for each sample. Both the MD and the CD were determined. Table 3 shows the testing results.

#### Surface roughness parameters: $R$ -MAD vs. $R_a$

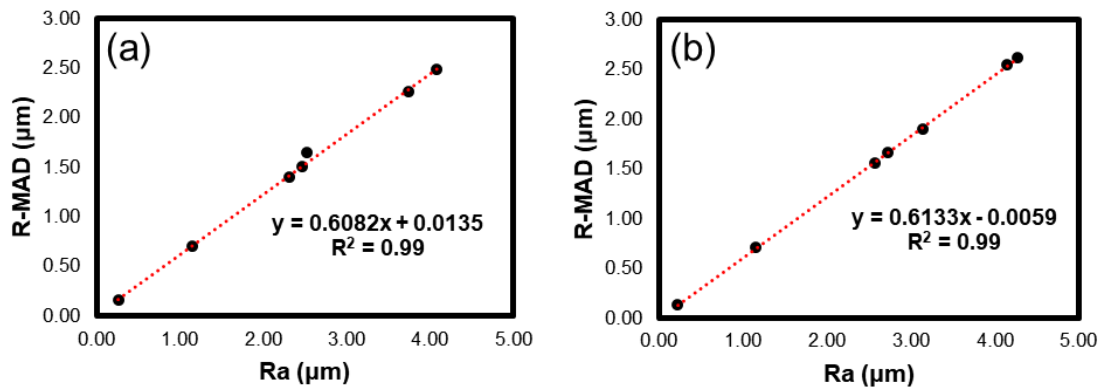
Figure 6 shows the plots of the  $R$ -MAD vs. the  $R_a$  in the MD and the CD, respectively. In Fig. 8, the regression equations are also shown, which indicated a high correlation, with an  $R^2$  value equaling almost 1.0. Meanwhile, the slopes were drastically less than one, which indicated that the  $R$ -MAD should be less sensitive to the changes in the  $R_a$  values.

This may be explained by the fact that while  $R_a$  is influenced by the instrument and its operating conditions employed in a stylus-type contact method,  $R$ -MAD should be

independent of them, representing the variation within the sample. Thus, *R-MAD* may be interpreted by the absolute variation of the surface roughness profile of the sample.

**Table 3.** Testing Results for Roughness

Code	Direction	$R_a$		<i>R-MAD</i>	
		Mean ( $\mu\text{m}$ )	COV (%)	Mean ( $\mu\text{m}$ )	COV (%)
R1	MD	2.47	7.9	1.50	5.1
	CD	2.72	3.5	1.67	3.7
R2	MD	2.52	23.5	1.64	3.6
	CD	3.15	3.5	1.90	4.2
R3	MD	2.30	4.3	1.40	3.7
	CD	2.58	6.8	1.56	9.1
R4	MD	4.08	12.0	2.49	13.1
	CD	4.15	21.3	2.55	21.2
R5	MD	3.75	7.9	2.26	6.2
	CD	4.27	5.5	2.62	6.5
R6	MD	1.15	8.2	0.70	10.2
	CD	1.16	7.5	0.71	8.7
R7	MD	0.26	4.8	0.16	7.2
	CD	0.22	10.5	0.14	11.5



**Fig. 6.** *R-MAD* vs.  $R_a$  (a: machine direction; b: cross direction)

### Determination of Friction

The average COF and *F-MAD* were calculated using Eqs. 4 and 5, respectively. The COV in percentage was determined from 10 measurements for each sample. Both the MD and the CD were determined. Table 4 shows the testing results.

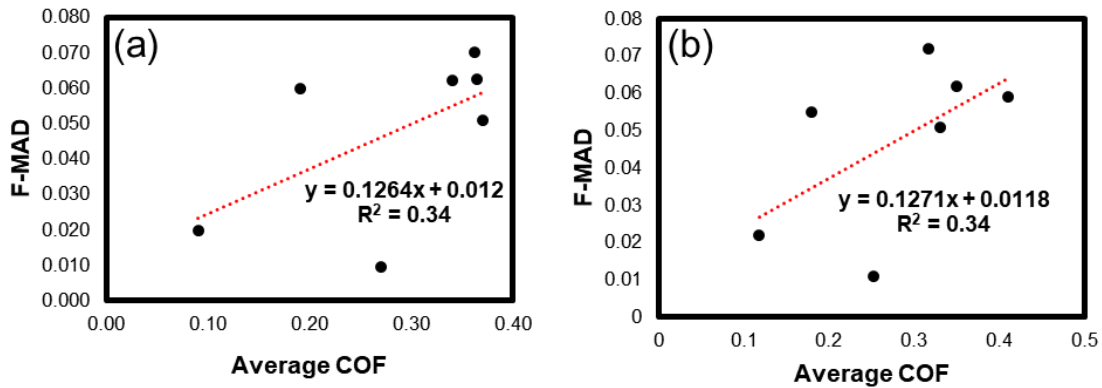
#### *Friction parameters: F-MAD vs. average COF*

Figure 7 shows the plots of the *F-MAD* vs. the average COF of the samples in the MD and CD, respectively. In contrast to *R-MAD* vs.  $R_a$ , the correlation between the *F-MAD* and the average COF was poor, with an  $R^2$  value of about 0.3, in both the MD and the CD. This strongly suggests that the *F-MAD* should be independent of the COF because the former measures the friction between the stylus and the sample surface, which depends on the instrument including its testing conditions. Meanwhile, it is noted that the *F-MAD* indicates the deviation from the average COF, which represents a variation for a sample,

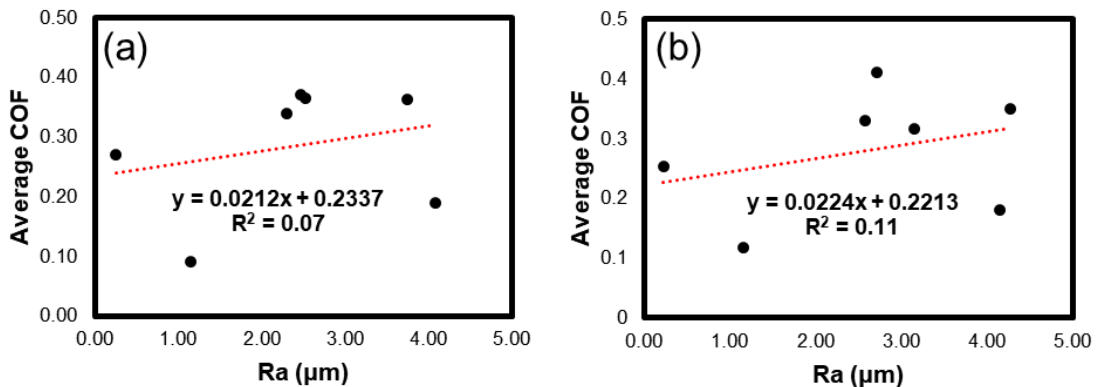
and it should not depend on the test conditions. Thus, F-MAD may be interpreted by the absolute variation of the friction profile of the sample.

**Table 4.** Testing Results for Friction

Code	Direction	Average COF		F-MAD*	
		Mean	COV (%)	Mean	COV (%)
R1	MD	0.37	18.7	0.051	10.3
	CD	0.41	31.7	0.059	27.1
R2	MD	0.36	22.2	0.63	20.7
	CD	0.32	12.4	0.72	17.0
R3	MD	0.34	16.3	0.062	24.0
	CD	0.33	20.3	0.051	23.3
R4	MD	0.19	31.3	0.060	22.2
	CD	0.18	17.7	0.055	18.8
R5	MD	0.36	15.8	0.070	13.4
	CD	0.35	12.6	0.062	11.1
R6	MD	0.09	33.7	0.020	17.5
	CD	0.12	27.7	0.022	17.4
R7	MD	0.27	8.0	0.010	10.1
	CD	0.25	8.8	0.011	17.1



**Fig. 7.** F-MAD vs. average COF (a: machine direction; b: cross direction)



**Fig. 8.** Average COF vs.  $R_a$  (a: machine direction; b: cross direction)



## Friction vs. Surface Roughness

### Average COF vs. $R_a$

Figure 8 shows the correlation between the average COF and the  $R_a$  in the MD and the CD, respectively. The correlation between the two values was extremely poor with an  $R^2$  value of almost zero in both cases (MD and CD). This suggested that the roughness and the friction should be independent of each other, as previously mentioned.

### $F$ -MAD vs. $R$ -MAD

Figure 9 shows the correlation between the  $F$ -MAD and the  $R$ -MAD in both the MD and the CD, respectively. The correlation was rather low, especially the five samples circled in the figure which show practically no correlation at all. This again supports the argument that the surface roughness and friction should be independent of each other

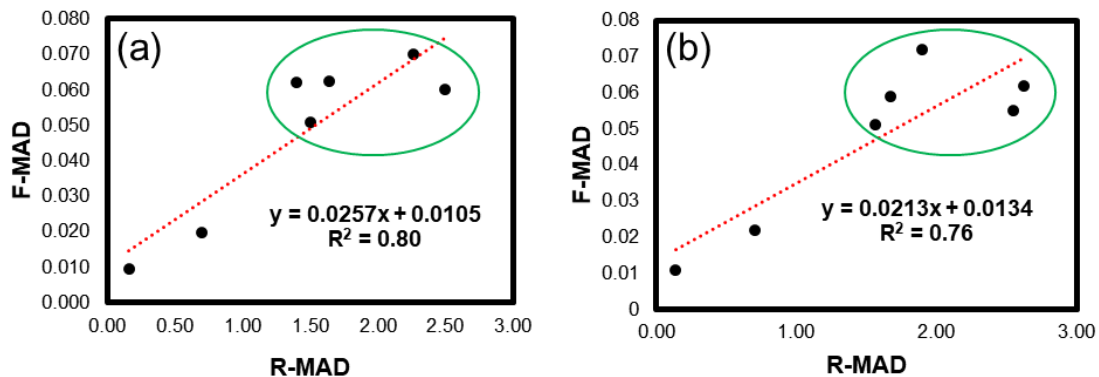


Fig. 9.  $R$ -MAD vs.  $F$ -MAD (a: machine direction; b: cross direction)

## CONCLUSIONS

In a stylus-type contact method, a conical-type stylus whose tip diameter of 1.0 mm at a contact force of 5 gf and a data acquisition rate of 100 Hz was found to provide the most stable and reliable profiles of surface roughness and friction for paper products.

Correlation between the roughness and friction was very low, with practically no correlation between the two. This suggests that the two should be independent of each other. Accordingly, determining both surface roughness and friction is required for the surface characterization of paper products.

As a new surface characterization parameter, the mean absolute deviation (MAD) was introduced: the  $R$ -MAD for the surface roughness and the  $F$ -MAD for the surface friction.  $R$ -MAD represents the deviation from the roughness average and  $F$ -MAD represents the average COF. While  $R_a$  or average COF depends on the instrument and its operating conditions,  $R$ -MAD or  $F$ -MAD should not depend on them because the latter represents the variations within the sample.

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